Toward Standardized Testing of Magnetic Materials, Cores and Components

Mark Nations[1], Bharadwaj Reddy Andapally[2], Prof. Paul Ohodnicki [3,4,5], Christopher Bracken[3]

[1] Electrical and Computer Engineering, North Carolina State Univ.
[2] Companhia Brasileira de Metalurgia e Mineração (CBMM)
[3] Mechanical Engineering and Materials Science, Univ. of Pittsburgh
[4] Electrical and Computer Engineering, Univ. of Pittsburgh
[5] Department of Physics & Astronomy, Univ. of Pittsburgh

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

CBMM – Nanocrystalline Soft Magnetic Materials (NSMM*) Development Center

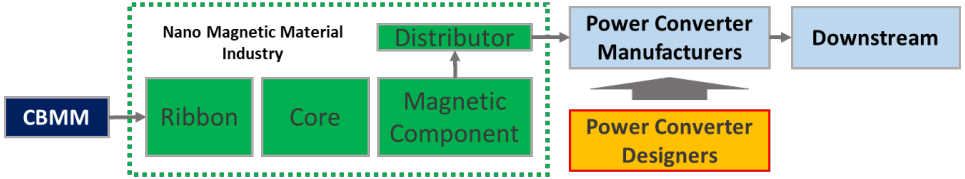
CBMM | Niobium Nb

World leader in the production and commercialization of Niobium products, CBMM has customers in over 40 countries. With heaquarters in Brazil and offices and subsidiaries in China, Netherlands, Singapore, Switzerland and the United States, the company supplies products and cutting-edge technology to the infrastructure, mobility, aerospace and energy sectors. CBMM was founded in 1955 in Araxá, Minas Gerais, and relies on a strong technology program to increase Niobium applications, growing and diversifying this market.

Further information can be obtained at **www.niobium.tech**

v06.2021 Copyright © 2021 CBMM

Nanocrystalline Material Development Value Chain



CBMM supplies essential raw material (Fe-Nb) to global nanocrystalline ribbon producers

CMC-Common Mode chokes
PFC Inductors (Nano powders)
DC Inductors (Nano powders)
C.T -Current Transformers

Grid filters
RCD – Residual Current Detectors
MFT – Medium Frequency Transformers

Value proposition of nano

COMPETITIVE ADVANTAGES
OF NANOCYSTALLINE

Material Advantages

- **Reduction in weight and size** — Up to a 50% reduction in weight and 75% reduction in size, leading to cost reductions compared to ferrite
- **Wider frequency range** — Nanocrystalline provides noise damping over a wider frequency range
- **Outstanding Thermal Stability** — Operational temperature stable up to 130°C
- **Improved damping at low freq.** — Better insertion loss/gain at low frequency and large rated current

Growing Market Trands for the use of NSMM*

- CMC and EMC for EV : On- board & Off -board applications ;
- Current Transformers for : Smart metering , Revenue metering , Data center BCM** , Industrial metering ;
- Differential Current Sensor for EV charging stations : RCD Type A + 6 mA DC sensor ;
- Medium frequency Transformer applications for high power electronics and solid-state transformers ;
- DC-DC inductors and PFC inductors using Nanocrystalline powder cores and stress annealed cores ;
- Wireless charging shields for mobiles and EV charging ;

**NSMM=Nanocrystalline Soft Magnetic Materials*

***BCM= Branch Circuit Monitoring*

Major Challenges for Growth of NSMM*

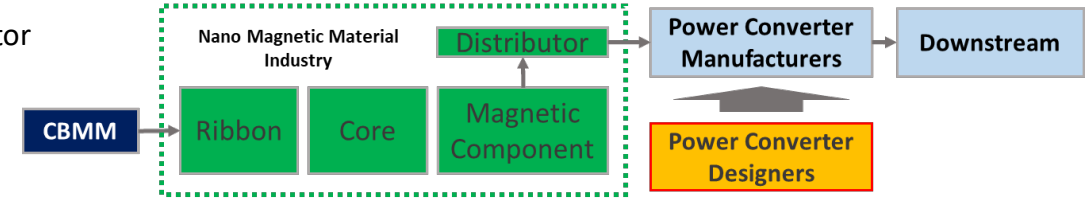
- Lack of awareness among the engineers on the material properties, its potential applications and the connection between producers and end users ;
- Negative perception in the market that NSMM is expensive and very hard to source these materials as they are only produced by limited number of companies;
- They are limited by shapes as they are tape wound cores ;
- They have lower Bs (1.2T) material compared to electrical steel (1.8T) ;
- They do not yet have any standardization protocols for testing and characterization of materials & cores ;
- Present NSMM* technology is not suitable for power applications(transformers and inductors) > 100KHz ;

*NSMM=Nanocrystalline Soft Magnetic Materials

CBMM Development Strategy for NSMM*

- Creating awareness through various platforms : CBMM is on a mission to disseminate the NSMM technology to as many power converter design companies and students who are the key decision makers on selecting right magnetic material for their projects ;
- CBMM supplies FeNb to NSMM ribbon producers , its position is in upstream. However, we would like to help in accelerating the market growth for NSMM. Therefore, our strategy is to work with all the stakeholders in the value chain from upstream to downstream;
- Sharing market knowledge on NSMM value chain : At this moment there are more than 100 companies around the globe who are involved in production of NSMM* ribbons and cores. 90 % of the producers are in Asia. Regions involved are China, South Korea, Japan, India, Germany, United states ;
- Investing in pilot studies/case studies with universities and industrial players to prove the benefits of using NSMM in emerging markets . Few such projects are :

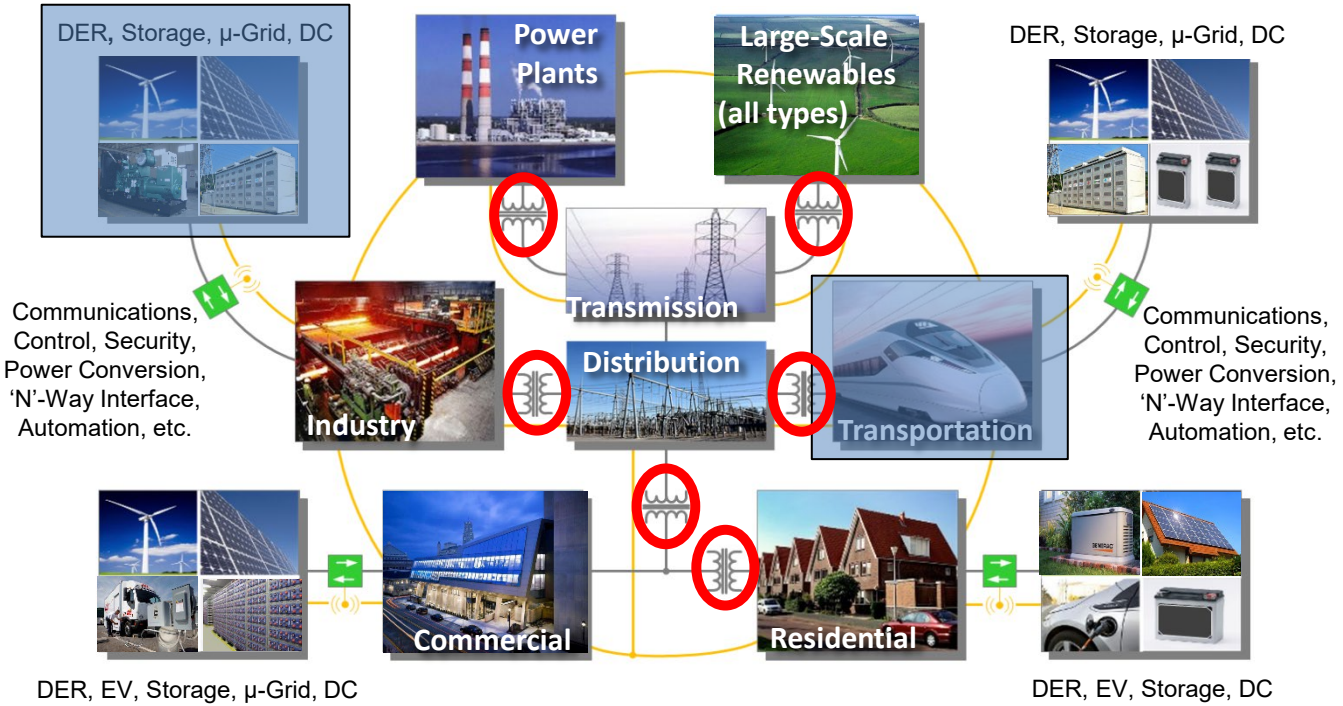
✓ High powder density electric motors using NSMM* stator
✓ NSMM testing and characterization
✓ High Bs (>1.5T) ribbon development
✓ Low permeability stress annealed cores
✓ High power density EV Onboard Chargers
✓ Nanocrystalline powder cores using gas atomization process



CBMM supplies essential raw material (Fe-Nb) to global nanocrystalline ribbon producers

*NSMM=Nanocrystalline Soft Magnetic Materials

Motivation: Electrification in the 21st Century

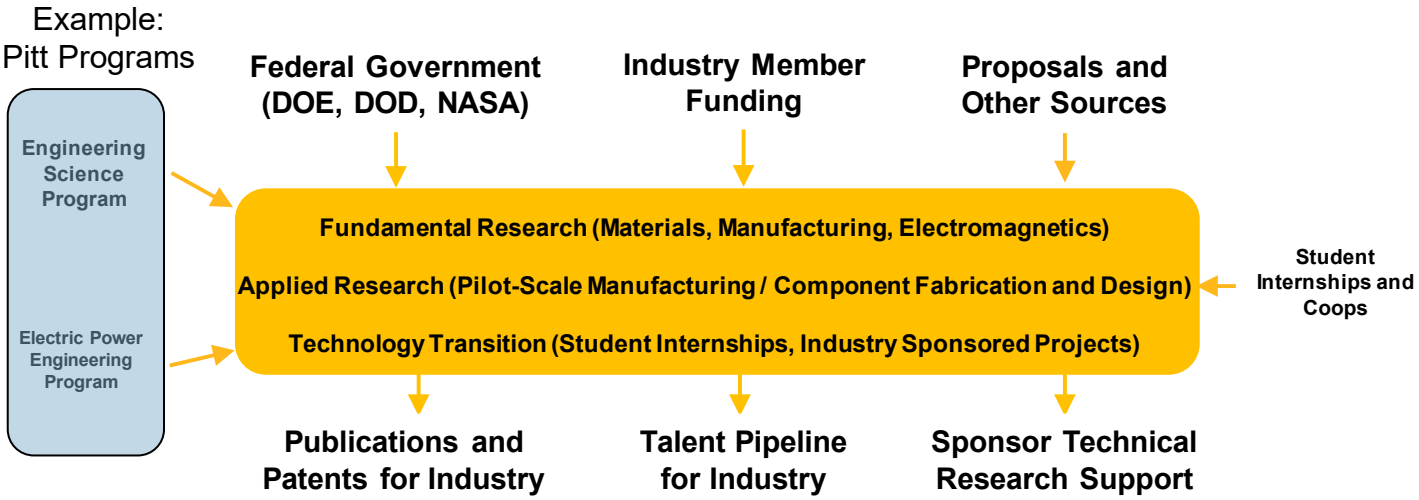


Challenge: A Need Exists for a Next Generation, Interdisciplinary Workforce and Targeted Research Support of Magnetic Devices (Transformers, Inductors and Electric Vehicle Motors)

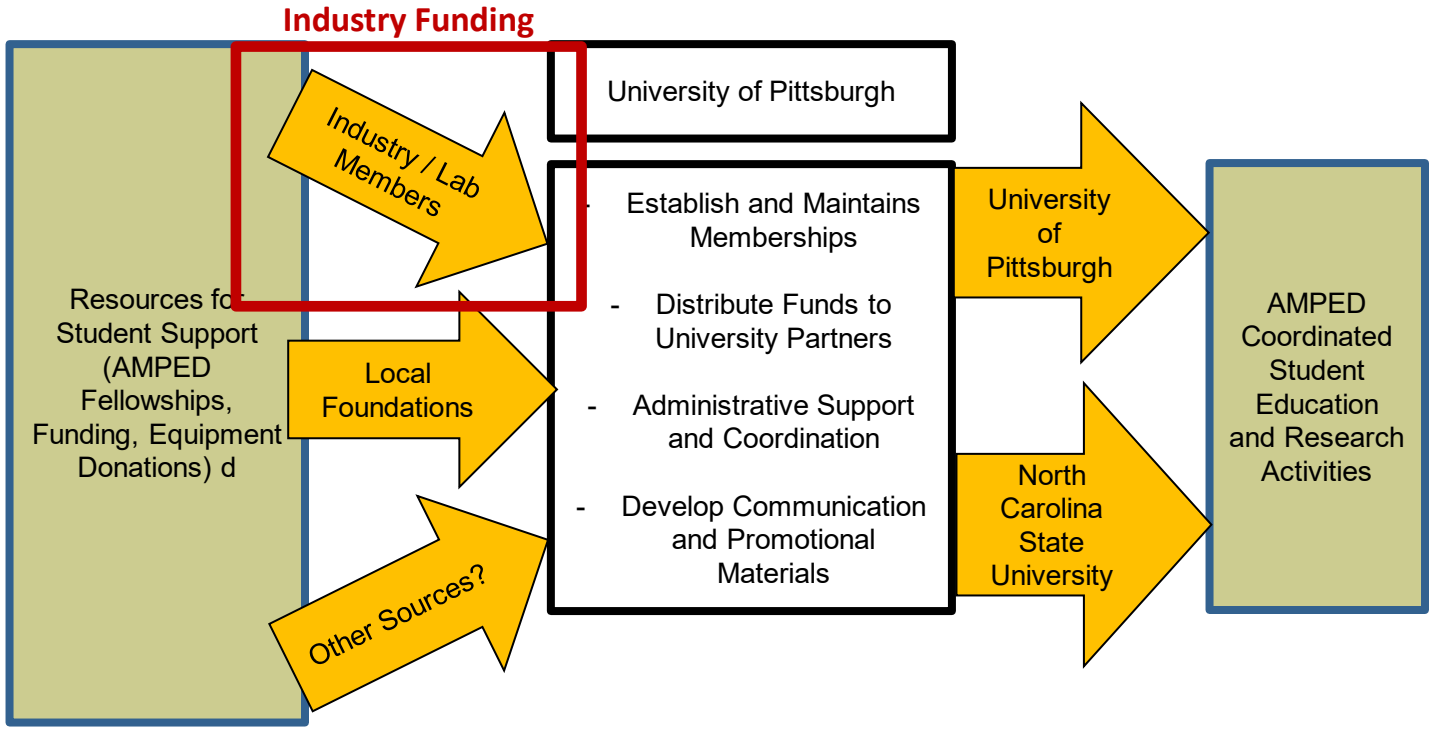
Advanced Magnetics for Power and Energy Development (AMPED)

Mission Statement

To develop an innovation ecosystem and educational programs for advancing soft magnetic materials and component technologies spanning fundamental science to end-use application in collaboration with various agencies, offices, and programs.



Advanced Magnetics for Power and Energy Development (AMPED)



Industry Funding Allocated as Follows: 25% - AMPED Lab, 75% - Each University

Advanced Magnetics for Power and Energy Development (AMPED)

Charitable Contributors

Ansys

COMPUTER AIDED TECHNOLOGY

KEYSIGHT TECHNOLOGIES

Lake Shore CRYOTRONICS

OMICRON LAB

TestEquity
Our brands: Techni-Tool | Jensen Tools

Full Participants

NAVAL NUCLEAR LABORATORY
75 YEARS

Bechtel Plant Machinery, Inc.
Quality, Integrity, Excellence

RCT SYSTEMS

GMW Associates

NASA

NAVAL REACTORS
N R

POWDERMET
ENGINEERED POWDER TECHNOLOGIES

EATON

L3HARRIS

U.S. NAVAL RESEARCH LABORATORY

NAVSEA
NAVAL SEA SYSTEMS COMMAND

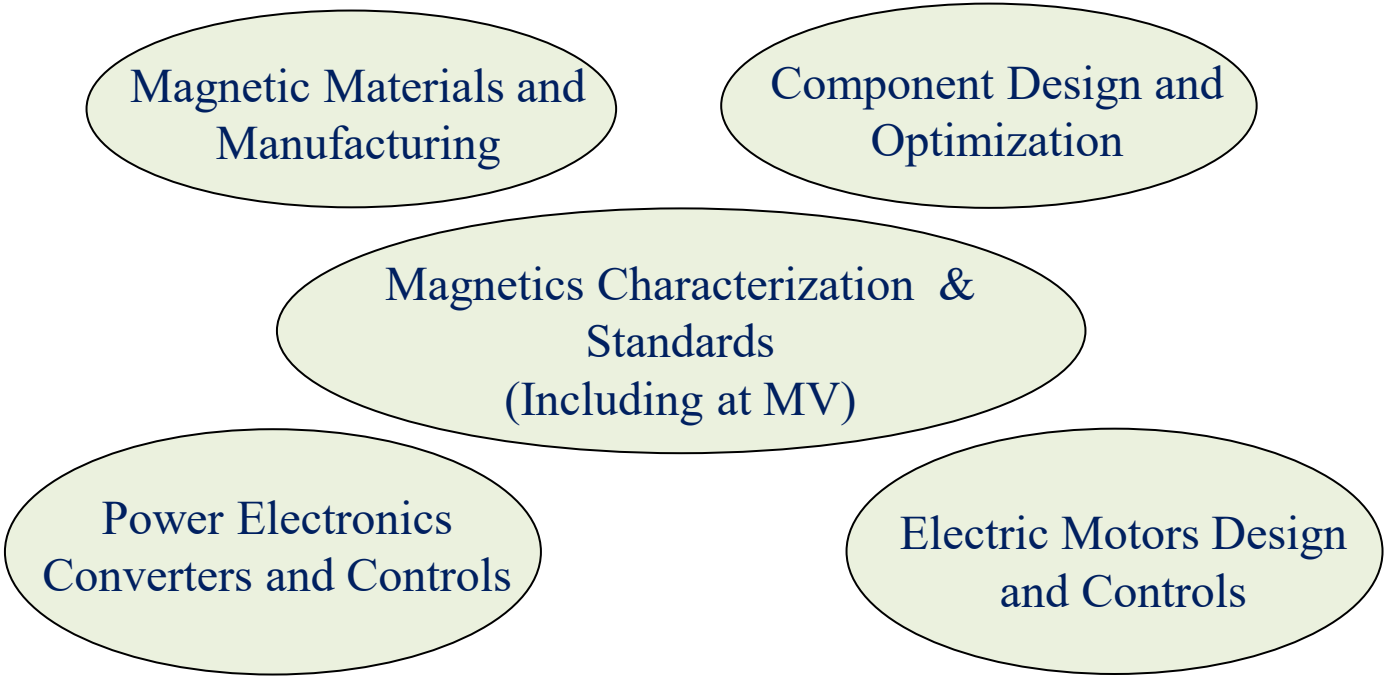
Metglas®, Inc.

Garrett
ADVANCING MOTION

Thank you to our founding participants and contributors!

Advanced Magnetics for Power and Energy Development (AMPED)

Core Capability Focus Areas Across Universities



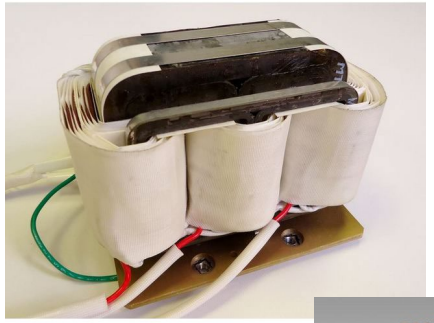
Key Focus Areas in AMPED : Based on Industry Input

Industry Sponsored Datasheet Development

University of Pittsburgh

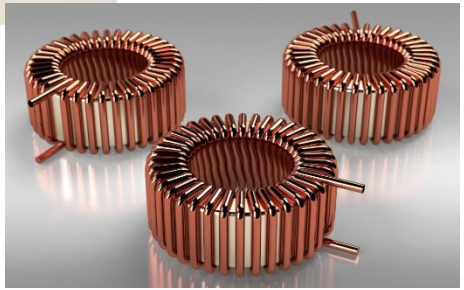
CBMM

- Bharadwaj Reddy Andapally
- Mariana Perez de Olivera



Three Applications:

- High Frequency Transformer
- Harmonic Filter / Line Filter
- Current Transformer



Two Core Types:

- Industry Standard
- Nanocrystalline

University of Pittsburgh – CBMM

- Standardized Testing of Materials and Electromagnetic Components
- Benchmarking of Nanocrystalline Soft Magnetic Cores vs. Industry Standard

Data Sheets - Core Materials

- Determine intrinsic core material properties which are independent of geometry.
- For tape-wound cores, measurements may be obtained by strip testers or inline permeability measurement.
- Priority data:
  - Losses vs. Frequency
  - Permeability vs. Frequency
  - Permeability vs. Field Strength
- Test Specifications
  - Excitation frequency $f \in$ (50Hz, 200kHz)
  - Flux density: $B_{pk} \in$ (50mT, 1T)
  - Temperature: $T \in (20°C, 150°C)$

Core Testing Standards

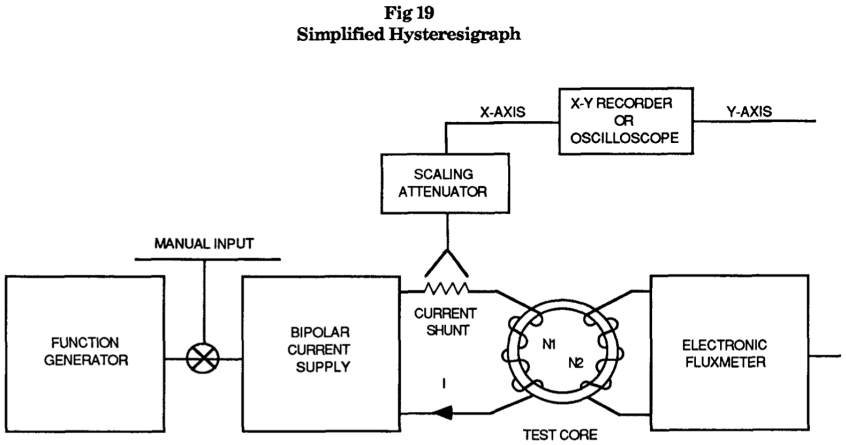
IEEE 393 : 1991 – IEEE Standard for Test Procedures of Magnetic Cores

- ✓ Section 5 – Analytical terminology definition (core loss, apparent core loss, permeability, etc.)
- ✓ Section 6 – Test procedures including two-winding method, bridge measurements, etc.

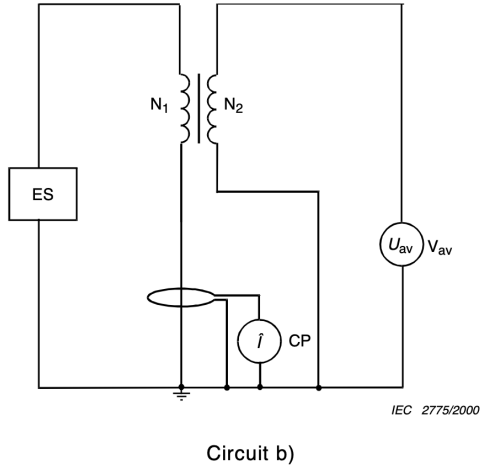
IEC 62044

- ✓ IEC 62044-1:2000 : Cores made of soft magnetic materials – Measurement Methods Part 1
  - ✓ Generic specifications
  - ✓ Defines basic testing principles, selection of coils, magnetic conditioning (electrical / thermal)
- ✓ IEC 62044-2:2000 : Cores made of soft magnetic materials – Measurement Methods Part 2
  - ✓ Magnetic properties at low excitation levels
  - ✓ Includes terminology and parameters for test setups using impedance analyzer / LCR meter
- ✓ IEC 62044-3:2000 : Cores made of soft magnetic materials – Measurement Methods Part 3
  - ✓ Magnetic properties at high excitation levels
  - ✓ Annex A and section 6 : show the two-winding method, Annex B shows RMS method

Core Testing Standards



IEEE 393:1991



Circuit b)

IEC 62044-3:2000 Annex A

Primary Measurements Required:

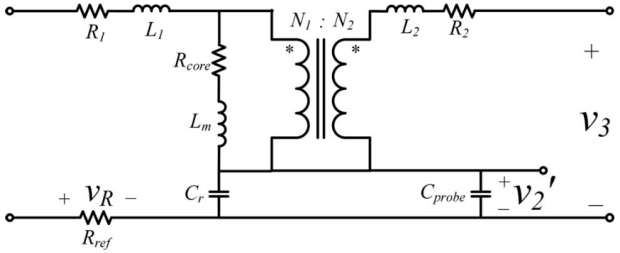
- ✓ Induced Voltage – Open Secondary Winding
- ✓ Applied Current – Primary Winding

Additional Considerations:

- ✓ Excitation Details (Voltage, Current, Waveform)
- ✓ Probes (Phase Shift, Linearity, Bandwidth)
- ✓ Environment (Temperature)
- ✓ Core Specifics (Material, Size, Shape, Manufacturing, Construction, Vendor…)

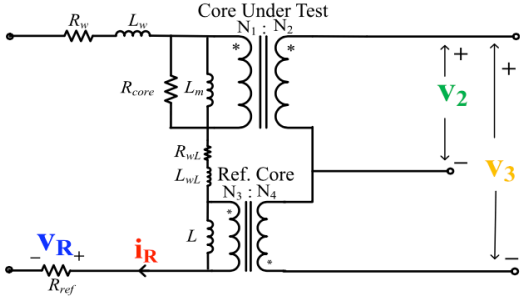
Core Testing Standards

Capacitive Cancellation Method



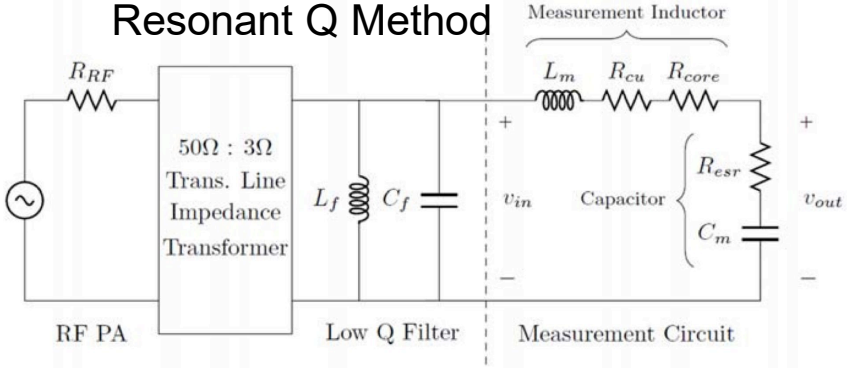
VA Tech : Sinusoidal Excitation

Inductive Cancellation Method



VA Tech : General Excitation

Resonant Q Method

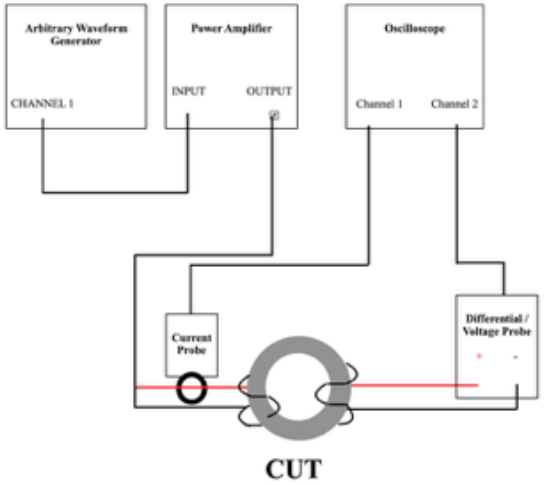


Dartmouth : High Frequency, General Excitation

-Hou, Mu, Lee, Li. *New High-Frequency Core Loss Measurement Method With Partial Cancellation Concept*

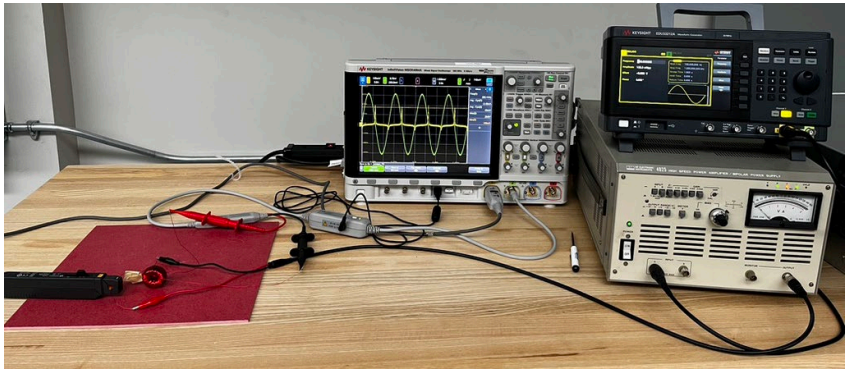
-Han, Y; Cheung, G; Li, A; Sullivan, C.R.; Perreault, D.J.; "Evaluation of Magnetic Materials for Very High Frequency Power Applications" in Power Electronics, IEEE Transactions on , vol. 27, no.1, pp.425-435

Data Sheets – Core Loss Measurements

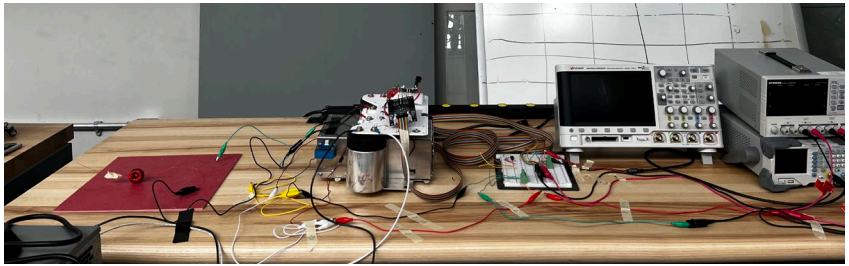


$$\mathrm{H}(t) = \frac{N_p i_p(t)}{l_m}$$

$$B(t) = \frac{1}{N_s A_e} \int_0^t V(\tau) d\tau$$



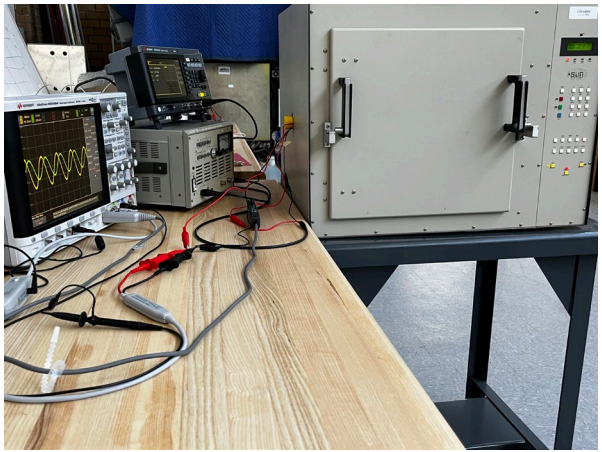
± 125V/ ±10A PA, Amplifier

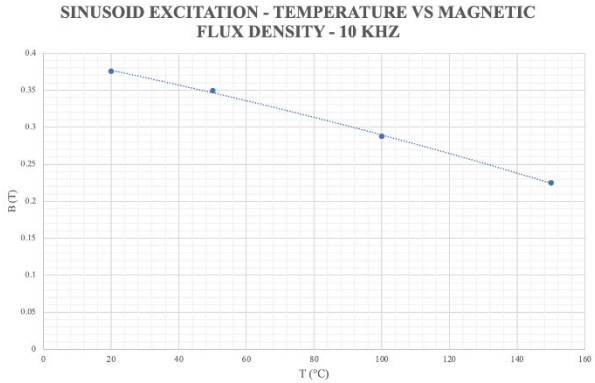


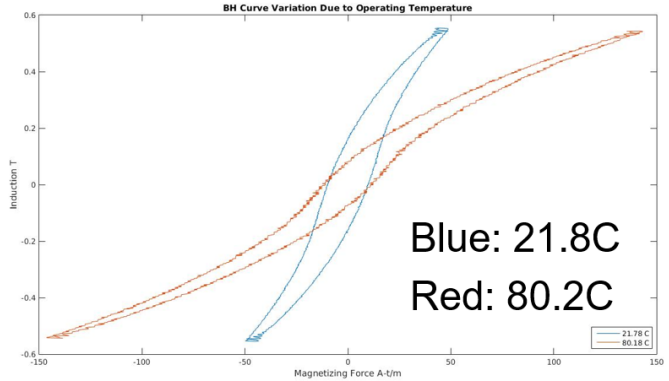
± 1.2kV/ ±100A, H-Bridge

Data Sheets – Temperature Testing

- Saturation flux density is the measured across the 20°C - 150°C temperature range.
- Temperature testing of manufactured cores can also capture the temperature dependence of permeability, and magnetostrictive effects.







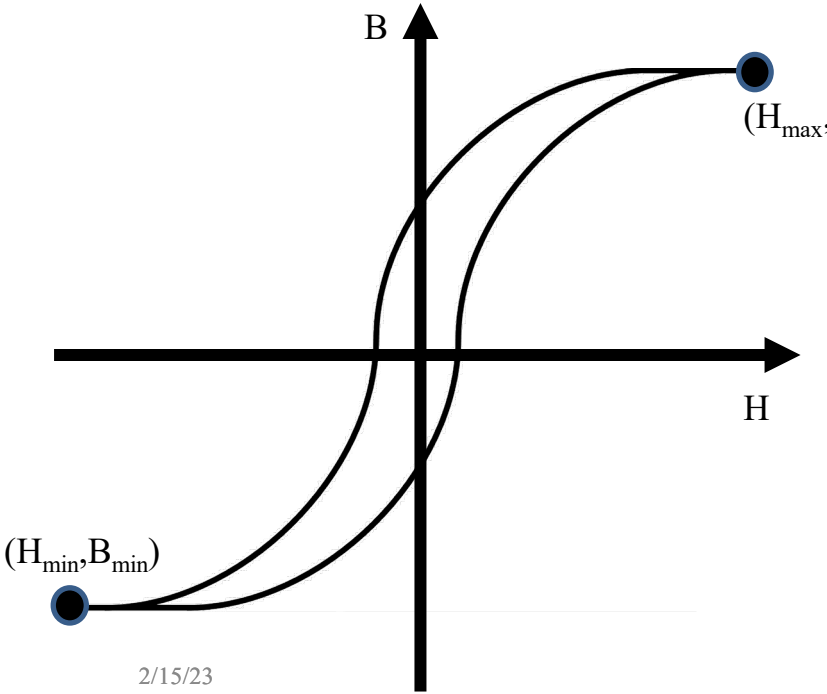
Data Sheets – Steinmetz Equation Fitting

$$P_w = k_w \left(\frac{f}{f_0}\right)^{\alpha} \left(\frac{B}{B_0}\right)^{\beta}$$

P_w = Core Loss per Unit Weight
f_0 = Base Frequency (use 1 Hz)
B_0 = Base Flux Density (use 1 T)
k_w = Steinmetz coefficient from empirical data
α = Steinmetz coefficient from empirical data
β = Steinmetz coefficient from empirical data

- Equation fits data based on hysteresis and eddy currents, linearized in logarithmic form.
- α, β, and k_w are obtained via simulation using MATLAB program developed by Dr. Scott Sudhoff of Purdue University.
- Once all parameters are obtained, fit evaluated at each frequency and flux density value through Excel.

Data Sheets – BH Loop Processing

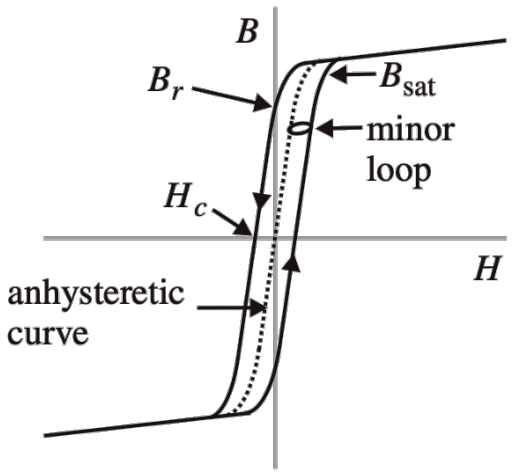


$$B_r = \frac{B_{max} + |B_{min}|}{2} \qquad H_r = \frac{H_{max} + |H_{min}|}{2}$$

$$\mu_r = \frac{B_r}{\mu_0 H_r} \qquad P_{l,sp} = \frac{f A_e l_e}{m} \int_0^{\tau} B \cdot dH$$

B_r = Relative Flux Density (T)
B_{max} = Maximum Flux Density (T)
B_{min} = Minimum Flux Density (T)
H_r = Relative Field Strength (A / m)
H_{max} = Maximum Field Strength (A / m)
H_{min} = Minimum Field Strength (A / m)
μ_r = Permeability of Free Space (4πE-07)

Data Sheets – Anhysteretic BH Loop



Power Magnetic Devices: A Multi-Objective Design Approach, First Edition. S.D. Sudhoff. © 2014 by the Institute of Electrical and Electronic Engineers, Inc.

- The anhysteretic BH is obtained using the Sudhoff/Shane program.
- Models the anhysteretic curve from given hysteresis plot.
- Model averages flux linkage from lower curve to upper curve.
- Three coefficients generated from fit , α, β, and γ, evaluating B.

$$B = \mu_B(B)H$$

$$\mu_B(B) = \mu_B \frac{r(B)}{r(B) - 1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^{K} \alpha_k |B| + \delta_k \ln(\varepsilon_k + \zeta_k e^{-\beta_k |B|})$$

$$\delta_k = \frac{\alpha_k}{\beta_k} \qquad \zeta_k = \frac{1}{1+e^{-\beta_k \gamma_k}} \qquad \varepsilon_k = \frac{e^{-\beta_k \gamma_k}}{1+e^{-\beta_k \gamma_k}}$$

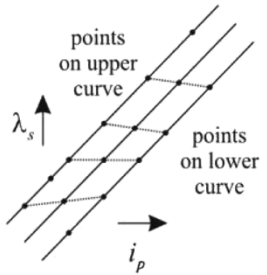
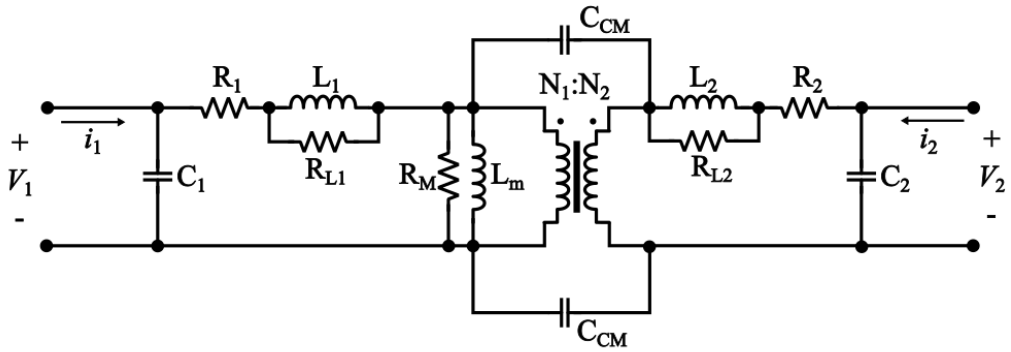


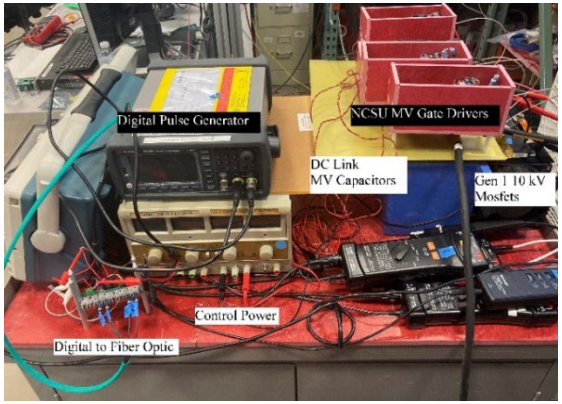
Fig. 3. Creation of "measured" anhysteretic $\lambda_s - i_p$ characteristic.

Grant M. Shane and Scott. D. Sudhoff, "Refinements in Anhysteretic Characterization and Permeability Modeling ," *IEEE Transations on Magnetics, Vol.46, No.11, November 2010.*

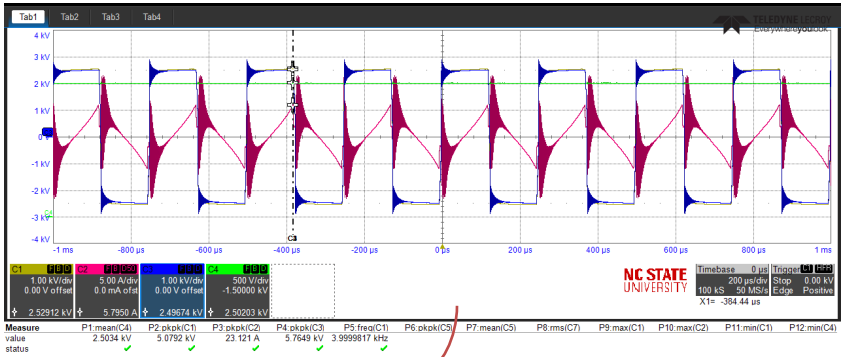
Component Level Testing a Black Box

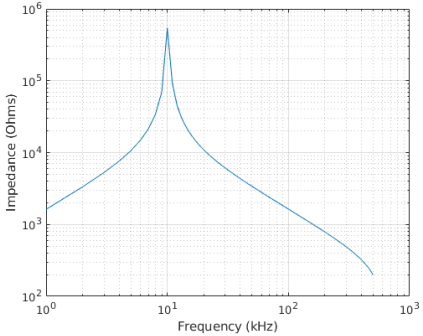
- Geometry and winding structure unknown
- Only terminal ports are available for measurements
- Approach:
  - Small signal impedance extracts lumped inductances and capacitances.
  - Winding induced voltages measure ‘large signal’ core characteristics.
- Excitation
  - Keysight E4980A Impedance Meter
  - 10kV, 10A Silicon Carbide H-Bridge. Tested up to 7kV, 8A, 20 kHz.



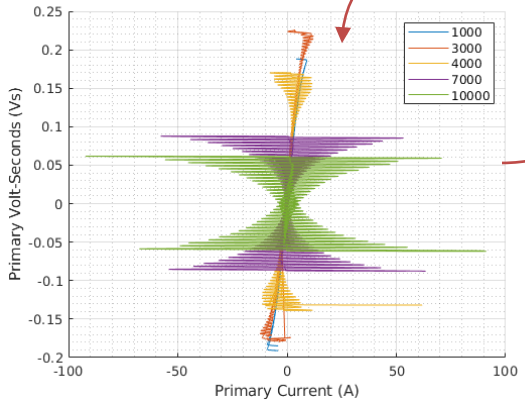


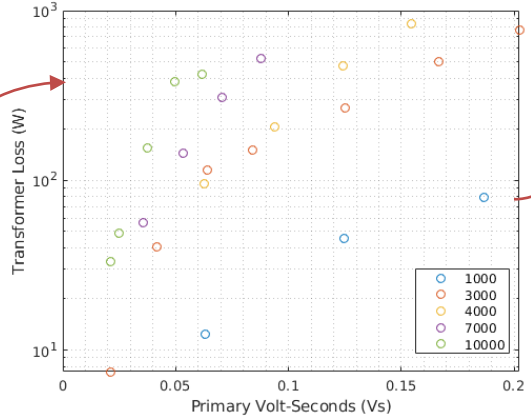
Black Box Component Measurements





- Impedance measurements determine lumped circuit elements.
- Self-resonant frequency is only ~10kHz with high quality factor.





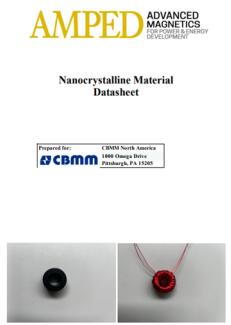
Steinmetz-like loss fit

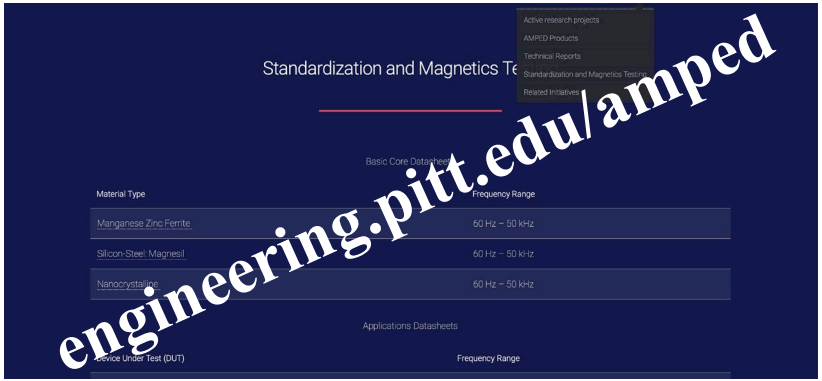
- $k = 0.206$
- $\alpha = 1.774$
- $\beta = 2.263$

Future Magnetic Standards

Datasheets

- “Data Transparency”
- Digitizable Data format. AMPED recommends formats of “.” “x”
- Plots AND Tables
- Current and Voltage Excitation Plots
- Photo of core and core with wires.
- Configuration section.
- Repeatable Procedure Developed
  - Test Setup Specifics, such as distance from Core to equipment.
  - Model drawings precisely of measurements and setups.
  - Test System Verification Setups and Procedures.
- Extra data essential for others to repeat or understand what exactly they are working with





Key Questions

- Which plots are most important to explicitly include within the data sheets?
- How can (and should) raw data be stored and made available for future designers?
- How can the measurement process be fully standardized?
- In what format / formats can the data be made compatible with various design tools (COMSOL, Ansys, PLECS, Simulink, Saber, etc.)
- How can the measurements be relevant for advanced core loss models?
- How can one distinguish / clarify material vs core geometry explicit properties in datasheets (i.e., Material Contrast of toroid, CC, EE cores versus datasheets for each core)?
- To what extent should advanced properties be characterized?
    - Pre-magnetization / DC Bias
    - Anhysteretic Measurements for Minor Loops
    - Temperature Dependences
    - Others?